Modeling Heap Leach Solutions to Optimize Safety and Revenue

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Abstract

For many mining projects, the most important water is not the effluent from a treatment plant or the fresh water supply, but the solution working its way through the Heap Leach Pad (HLP). Heap leaching of both gold and copper minerals produce their revenue from the interactions between water and ore. Unsaturated-zone groundwater modeling platforms allow for the accurate and effective prediction of the flow-through behavior of leach solutions within HLPs. GRE has applied this methodology on a gold heap leach pad using agglomerated ore. The simulation was used to optimize the leaching process and to aid in geotechnical and environmental safety analysis.

Keywords: Heap leaching, gold, unsaturated flow, agglomeration, groundwater flow simulation.

Introduction

Heap leaching is often the most cost-effective way to extract value from gold or copper ores. Heap leaching involves placing ore-grade material on an impermeable liner foundation with a solution collection system of drainpipes and irrigating the surface with either cyanide solution (for gold) or acid (for copper). Within the heap, chemical reactions occur which liberate the payable metal from the rock. The resultant solution, called pregnant leach solution (PLS), reaches the liner and the collection pipes, and then reports to a storage facility (pond) for processing where the metal is removed, the solution conditioned, and re-applied to the HLP as barren leach solution (BLS).

Flow modeling is an especially useful tool in HLPs with low conductivity ore. Low conductivity can occur for a number of reasons, but at this HLP, there are high proportions of fine or swelling clay minerals. Agglomeration is a process employed prior to leaching to improve solution conductivity. Agglomeration involves adding a binder, along with water or fresh lixiviant, to the crushed ore in a tumbling cylinder to bind fine-grained particles into gravel-sized material. The formation of agglomerates helps to improve the solution flow through the HLP.

Objectives

GRE has utilized modern unsaturated flow modeling platforms to better-understand the dynamics of heap leach flow in order to resolve several issues within an HLP. Specifically, simulations were performed to determine:

- If under-leached zones exist from poor solution distribution;
- If the pad had saturated zones which may impact geotechnical stability;
- If excess head was accumulating on the liner, augmenting the risk of a PLS leak through a pinhole-sized failure in the liner;
- If agglomeration process was adequate to ensure good leaching solution flow; and,
- If special conditions may detrimentally impact the operation or safety of the HLP.

Understanding the issues above is essential to the safe and profitable operation of an HLP.

Background

The flow in an HLP is dominated by unsaturated flow (Sheikhzadeh, 2005). Unsaturated flow is different from saturated flow because hydraulic conductivity is a non-linear function of the material moisture constant (Equation 1), rather than a constant. As a result, the practitioner must define the function of the conductivity of the material over a range of possible moisture contents of the materials. This is done through the application of the Van Genutchen equation and the Genutchen-Mualem model (Gurdal & Benson, 2003):

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1+(\alpha\psi)^n}\right]^2 \quad (Eq.1)$$

$$K_\psi = K_s \frac{\{1-(\alpha\psi)^{n-1}[1+(\alpha\psi)^n]^{-m}\}^2}{[1+(\alpha\psi)^n]^{\frac{l}{2}}} \quad (Eq.2)$$

Where:
θ_r = residual water content (≈ 0)
θ_s = saturated water content (equals porosity),
K_ψ = unsaturated hydraulic conductivity (as a function of soil matric suction)
K_s = saturated hydraulic conductivity
α, n = parameters fitted to Soil Water Characteristic Curve data (m= 1-n-1) (see below).
l = pore interaction term (0.5 for coarse grained soils)
These parameters can be derived from soil testing.

Methods

The process of unsaturated flow modeling is similar to other groundwater modeling projects that include: data collection, data analysis, model creation, model calibration, and predictive simulations. The system under investigation is a gold ore with significant argilized clay minerals that are crushed to a P80 of 12.5mm and agglomerated with cement, lime, and barren leach solution.

The agglomerates are conveyor stacked on the HLP and allowed to cure for 24 hours before solution application.

Data collection involved the collection of geotechnical and hydrogeologic data on the heap material. GRE collected a sample of the agglomerated ore and submitted it for the following laboratory test work:

- Gradation (ASTM D4318-17e1, 2018; D6913-04, 2017)
- Atterberg (ASTM D4318-17e1, 2018)
- Saturated Hydraulic Conductivity (Ks) (D5084-16a, 2019)
- Soil water Characteristic curve (SWCC) (ASTM D6836-16, 2016)

Of these variables, the K_s and SWCC are the most important for flow modeling. The SWCC is a curve which shows how the heap material retains moisture at various matric suction levels and it is an essential input to unsaturated flow modeling. The laboratory-derived SWCC was fitted to the Van Genutchen equations using a least squares minimization technique derived by (Gurdal & Benson, 2003).

Figure 1 is interpreted as follows:

- The saturated moisture content is ~30%.
- The material has a wide range of soil pore sizes. This can be seen because the overall slope angle of the SWCC is generally low. Conversely, homogenous materials typically have a very steep SWCC at a particular suction, meaning that all the water is held in a homogenous-sized pore space.

***Table 1** Gradation of the Agglomerated Ore on the Heap*

Size (mm)	% Passing	Description	Percentage
37.5	100	Coarse	
Gravel	7.83		
25.0	98.6		
19.0	92.2		
9.5	61.6	Fine Gravel	51.75
4.75	40.4		
2.0	25.3	Coarse Sand	15.17
0.85	13.0	Medium Sand	17.55
0.425	7.7		
0.25	5.5	Fine Sand	4.65
0.15	4.2		
0.075	3.1		
<0.075		Silt or Clay	3.06

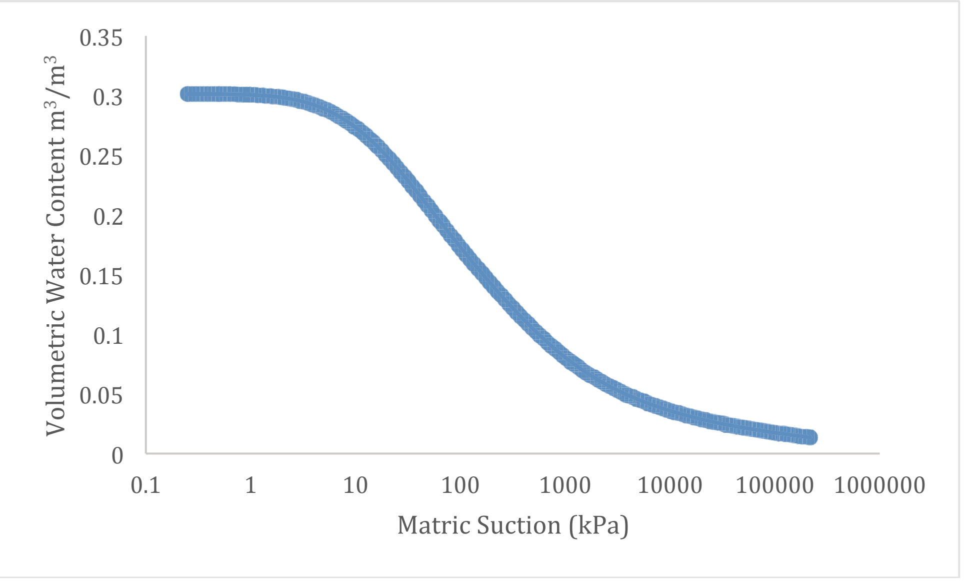

Figure 1 Soil Water Characteristic Curve for Agglomerated Gold Ore

- The material is largely fined-grained. This can be seen from the gentle slope of the upper right side of the SWCC curve.
- Residual moisture is 5%. This moisture appears to be held in clays, and cannot be removed without very high suction, if at all.

For the simulation, GRE utilized the GeoStudio SEEP/W modeling platform. This software is a finite-element groundwater modeling platform, which is fully compatible with slope stability analysis. Within this platform are tools to enter the SWCC as well as tools to derive the *K-θ* curve. As mentioned above, in unsaturated flow, hydraulic conductivity is a function of moisture content (see Eq. 2). This is a non-linear relationship called the K-theta (*K-θ*) curve; where theta is the moisture content of the soil, and where K is the conductivity (in m/s). SEEP/W will derive a *K-θ* curve for the agglomerated ore based on the Van Genutchen parameters. The heap material *K-θ* curve is shown in Figure 2.

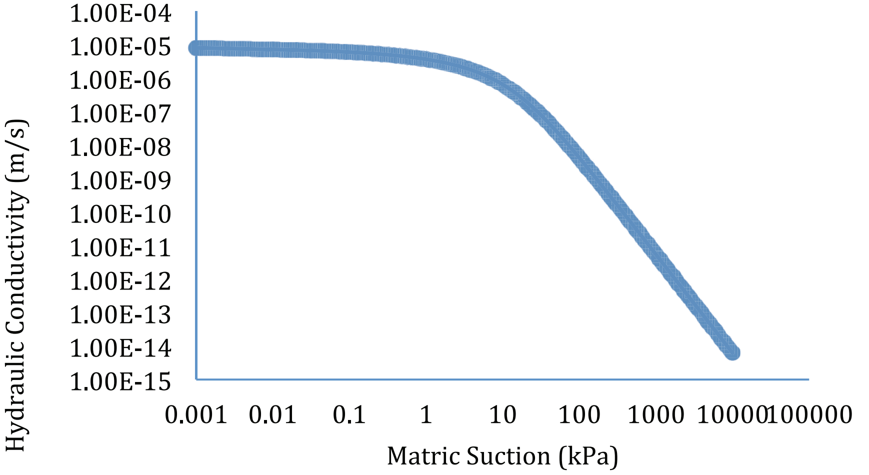

Figure 2 Moisture vs. Hydraulic Conductivity K-θ *Curve for Agglomerated Ore*

The *K-θ* curve is used by the groundwater modeling program to determine the conductivity at each model node based on the moisture content. The saturated hydraulic conductivity testing of the heap material had results from 8.1×10^{-4} cm/s to 1.7×10^{-4} cm/s, and Figure 2 shows how that conductivity decreases as a function of matric suction. The moisture-dependent conductivity value is then substituted into the flow simulation for each step and each node in the model.

GRE simulated a two-dimensional (2D) cross-section through the heap for unsaturated flow analysis; this section corresponds to the "critical slope" for slope stability analysis. The simulation included definitions for the ore heap, the liner, collection pipes, and the proper surface application rate of leach solution. A particle tracking program (CTRAN/W, also from GeoStudio) was used to track the time it took for a particle within the leach solution to flow to the collection pipes at the bottom of the pad. Only transient (time-variant) models are useful for this application.

Results

The model simulated the solution flow through the HLP and predicted areas that are both fully-saturated and under-saturated. Figure 3 shows an example of the results for the base case conditions with K = 8.0×10^{-4} cm/s and the drainage system performing as designed. The irrigation application rate employed was 9.78 L/hr/m^2.

In Figure 3, the image is focused on the most-interesting part of the simulated domain. The "warmer colors" show the higher moisture content, and the dashed blue line shows the developing water table. The results of the base case show the following:

- There is a flooded zone at the top of the HLP (as indicated by the blue shading above the ground surface) This is not best-practice and indicates an area where the leach application rate should be decreased.
- There is a phreatic surface accumulating on the liner in the upper part of the slope. This may impact the stability of the HLP by reducing the strength of the material. As mentioned above, it may also increase the risk of PLS leakage through the liner.
- One can see migrating moisture fronts within the HLP. These are the natural processes of wetting the material, increasing the conductivity, and establishing flow.
- There are no obvious under-leached areas in this heap. Most of the ore is fully wetted and near saturation.
- For the average HLP height of 50 or 60 meters, it takes 35–40 days for the solution to flow to the liner and piping system.

The results will be further discussed on the next page.

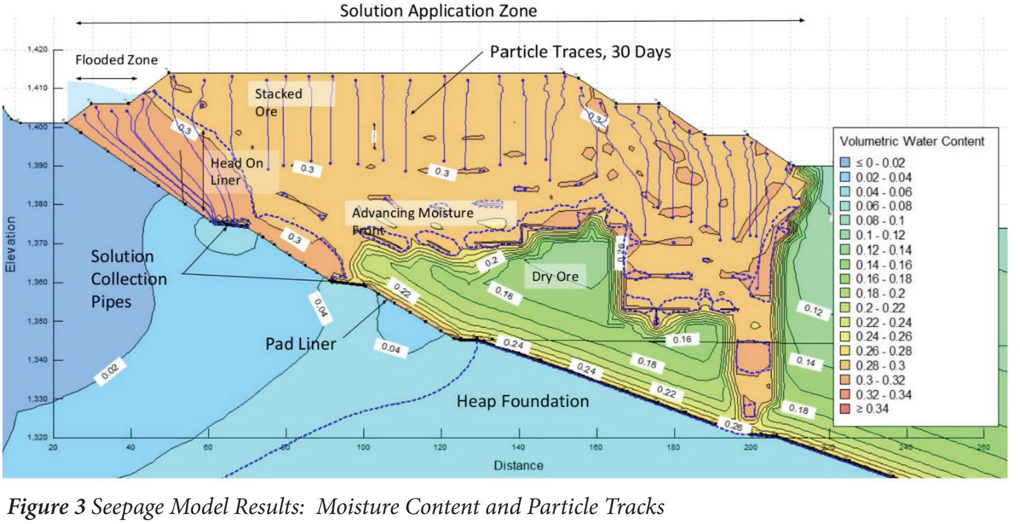

Figure 3 *Seepage Model Results: Moisture Content and Particle Tracks*

Discussion

The role of HLP modeling is to increase the stability and safety of the HLP, and to increase revenue by optimizing leaching. As a result, the base-case may not be the most-important simulation. The model allows the user to look at the impact of less-than optimal conditions on the dynamics of HLP flow. As a result, the model was used to simulate the following design permutations:

- Broken/collapsed collection pipes
- Lower conductivity (resulting from more argilized clay in the ore or poor agglomeration performance)
- Extreme precipitation atop the heap during leaching
- Observation of under-leaching

As discussed above, the base case model (Figure 3) already showed excess head on the liner which does not match best practice. With broken pipes, the head on the liner increased. As a result, GRE recommended a more robust pipe and underdrain design in the upper part of this HLP cross section.

Simulations at the lower conductivity range of the permeability testing (1.7 10^{-4} cm/s) resulted in a flooded model. Ponding on the surface is a problem with many heaps containing argilized ore (Lewandowski and Kawatra, 2009). GRE believes that this HLP's application rate requires a saturated conductivity at the high end of the agglomerated ore tested in the lab, at approximately 8×10^{-4} cm/s. As a result, GRE would recommend a reduced maximum irrigation rate and/or a strict design criterion establishing a minimum conductivity value for the agglomerated ore on the HLP.

For the extreme precipitation case, GRE was able to simulate a 100 year, 24-hour storm event falling atop the HLP. Results showed that, when compared to the leach application rate, extreme precipitation events did not appear to greatly change the leach solution moisture content nor the collection rate at the bottom of the HLP. The high water storage capacity of the agglomerated ore can easily accommodate the extra water without substantially changing the flow dynamics. As a result, the site does not need to modify solution collection piping or the emergency pond size to safely contain the 100-year storm event.

This project had a 45-day leaching cycle. An additional 45 days after the leaching cycle has ended, the HLP is largely drained down to its static moisture level of 22%. However, particle tracking analysis with CTRAN/W shows that the solution at the top of the HLP does not make it to the collection pipes before it gets "stranded" by matric suction (see particle traces, Figure 3).

This behavior indicates that stranded solution in the HLP could hold metal that would not be recovered. Depending on the grade of the solution it could be a significant revenue delay. A longer leach period may yield higher recovery by displacing this locked solution with lower grade barren solution, and maintaining the conductive high-moisture conditions for a longer period of time. The flow dynamics of a PLS particle is further complicated by secondary leaching, where solution from fresh upper lifts flows downward into lower ore zones where additional leaching occurs. As a result, using flow modeling with other process models like MetSim® can allow for a more in-depth understanding of the flow regime and the potential recovery impacts (Marsden, and Botz).

Because HLPs are often difficult to build and permit, miners have a strong incentive to stack as much ore on an HLP as is possible, yet HLP geotechnical stability is an essential element of operational and environmental safety. In this case, the moisture distribution and phreatic surface outputs from the seepage model were utilized to calculate heap stability. In this case, the high phreatic surface on the uphill liner (from meter marker 0–100 in Figure 3) did not have a significant impact on HLP stability.

Conclusions

The use of unsaturated flow modeling can be a powerful tool in understanding HLP operations. The proceeding example shows that simulations can aid in the geotechnical stability evaluations, the environmental safety, and the profitability of HLP operations. GRE also believes it is useful to expand the focus of mine water studies from the traditional environmental or water supply fields to a study of the type of mine water that mining operations care about the most – the leach solution that provides the metal.

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